Antiproton Working Group Report

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1 Introduction

The antiproton source at Fermilab was designed and built to collect antiprotons for use at high energy in the Tevatron Collider, and it is currently used only for this purpose. The charge of Working Group 5 was to envision the role that the antiproton source might play after the construction of a new high intensity 8 GeV proton source.

For the foreseeable future, the Tevatron Collider will operate at the highest possible luminosity and will use all of the antiprotons that the antiproton source can provide. This is likely to be the case even after a Proton Driver is built, since the estimate presented at this workshop (by Paul Derwent) is that the Proton Driver will at most allow a doubling of the antiproton stacking rate over the rate projected for the end of Run II.

If the Tevatron Collider ceases operation, or if a decision is made to operate the Collider at lower than maximum luminosity, then the antiproton source may become available for other purposes. At that time, there will likely exist only one, or possibly two, other antiproton sources in the world - one at GSI, and possibly one at CERN. It was in this context that the we considered the following possibile uses for the Fermilab antiproton source:

- A quarkonium formation experiment.
- A search for CP violation in hyperon decays using $\overline{p}p \to \overline{\Lambda}\Lambda$.
- Experiments with stopping antiprotons, including antihydrogen studies.
- The use of the Debuncher ring as a prototype neutrino factory.

2 Quarkonium Formation

The study of the charmonium and bottomonium systems has been crucial in unraveling the short-distance properties of the strong interaction. While most of the data have come from electron-positron interactions, a significant number of important measurements have been made in studies of antiproton-proton formation of charmonium. The rationale for the latter method is twofold. First, only 1^{--} states are directly formed by e^+e^- annihilation, although 0^{++} and 2^{++} states are formed in two-photon interactions, the latter with rather poor luminosity and resolution characteristics. Other states must be studied in 1^{--} decays, with correspondingly poor mass and width accuracies. Further, some of the most important states are difficult to reach in 1^{--} decays, such as the 1^{+-} and 0^{+-} states. In particular the h_c and η_c' states are reported but unconfirmed, and the h_b, η_b and η_b' states are undiscovered. In $\bar{p}p$ formation all non-exotic mesons can be formed. Second, because of synchrotron radiation losses, the energy spread in e^+e^- colliders is large (several MeV). In an antiproton storage ring, the energy spread can be 10-100 keV. This allows accurate and precise measurements of heavy-quarkonium masses and widths. The disadvantages in $\bar{p}p$ annihilations are small cross sections and accessibility of only several easily-identified modes because of the very large hadronic background. However these modes include decays to states including leptons, photons and kaons which are particularly important in heavy-quarkonium physics. Experiments R704 at CERN and E760-E835 at FNAL have successfully studied the charmonium spectrum, making the definitive measurements of masses, widths and branching ratios to two photons. A byproduct of this work is proton structure and light hadron spectroscopy.

There are important open questions in both charmonium and bottomonium that could be resolved by an experiment using $\bar{p}p$ formation. In charmonium the h_c must be confirmed, the significant mass discrepancy between the BELLE and BABAR sightings of the η_c' resolved, the h_c and η_c' widths measured, and the other narrow states identified and characterized, namely the $\eta_{c2}(1^1D_2)$, $\psi_2(1^3D_2)[X(3872)?]$, 1^3D_3, 2^3P_2, and 1^1F_4. The bottomonium 1S, 2S, 1P and 2P singlet states are unobserved and the 1P and 2P χ_b masses have been measured at the 1 MeV level, but the widths are not yet measured. D states of bottomonium have not been observed.

The interesting charmonium measurements could be made using a gas jet target in the Antiproton Accumulator, with a spectrometer similar to the E835 spectrometer. At least part of the E835 spectrometer could be reused. In order to study bottomonium, it will be necessary to build a new facility. The branching ratio of bottomonium states to $\overline{p}p$ have not yet been measured, so the formation cross section for bottomonium is not known, but it is expected to be small and the states are narrow, thus high luminosity and very small beam energy spread are required. We expect, for example χ_b formation cross sections to be no larger than $\sim$1 nb and χ_b widths to be $\sim$ 100 keV [1]. Therefore, The instantaneous luminosity should be at least 10^{32} cm^{-2}s^{-1} and the $s^{1/2}$ resolution $\sigma_E < 100$ keV.

In the previous CERN and FNAL experiments, a hydrogen-gas-jet target intersected a high-current cooled stored $\bar{p}$ beam; E835 reached $L \sim 5 \times 10^{31}$ and $\sigma_E \sim 100$ keV at charmonium energies. A similar bottomonium experiment would require a $\bar{p}$ storage ring with variable energy between 46 and 56 GeV with $\Delta p/p \sim 10^{-5}$. It would be relatively difficult to operate at charmonium energies of 3-8 GeV. Because of the higher beam energy, a bottomonium detector would require acceptance at smaller angles than a charmonium detector.

An alternative design would be a symmetrical $\bar{p}p$ collider operating at 4.5-5.5 GeV per beam, again with $\Delta p/p \sim 10^{-5}$. It appears plausible to achieve the required luminosity. Such a machine could be designed to operate at charmonium energies at a smaller luminosity, which would be acceptable for that physics. We note that this machine would fit nicely into the Booster tunnel, which will be available when the Proton Driver is complete. The detector would be similar to CLEO III, and it is conceivable that the CLEO III detector will be available for this use.

3 CP Violation in Hyperon Decays

The Standard Model (SM) predicts a slight *CP* asymmetry in the decays of hyperons [2–5]. The most accessible signal, the fractional difference in the magnitudes of the α decay parameters [6] for a hyperon and its antiparticle [3, 7], is predicted in the SM to be of order 10^{-5} for Λ decay [2–5]. In various extensions of the SM these can be much larger; for example, the supersymmetric calculation of He *et al.* [8] generates asymmetries as large as 1.9×10^{-3}. Sensitive measurements of hyperon and antihyperon decay can thus provide a new window into the underlying mechanism of *CP* violation.

Table 1 summarizes the experimental situation. The first three experiments cited studied Λ and $\overline{\Lambda}$ decay only [9–11]. Fermilab experiments E756 [12] and HyperCP (E871) [13, 14] and CLEO [15] employed the cascade decay of charged Ξ and $\overline{\Xi}$ hyperons to produce polarized Λ's and $\overline{\Lambda}$'s, in whose subsequent decay the (anti)proton angular distribution measures the product of α_Ξ and α_Λ.

Table 1: Summary of experimental limits on *CP* violation in hyperon decay.

Expt.	Facility	Mode	A_Λ [*] or $A_{\Xi\Lambda}$ [†]	Ref.
R608	ISR	$pp \to \Lambda X, pp \to \overline{\Lambda} X$	$-0.02 \pm 0.14^*$	[9]
DM2	Orsay	$e^+e^- \to J/\psi \to \Lambda\overline{\Lambda}$	$0.01 \pm 0.10^*$	[10]
PS185	LEAR	$\overline{p}p \to \overline{\Lambda}\Lambda$	$0.006 \pm 0.015^*$	[11]
E756	FNAL	$pN \to \Xi^- X, \Xi^- \to \Lambda\pi^-$, $pN \to \overline{\Xi}^+ X, \overline{\Xi}^+ \to \overline{\Lambda}\pi^+$	$0.012 \pm 0.014^\dagger$	[12]
CLEO	CESR	$e^+e^- \to \Xi^- X, \Xi^- \to \Lambda\pi^-$, $e^+e^- \to \overline{\Xi}^+ X, \overline{\Xi}^+ \to \overline{\Lambda}\pi^+$	$-0.057 \pm 0.064 \pm 0.039^\dagger$	[15]
HyperCP‡	FNAL	$pN \to \Xi^- X, \Xi^- \to \Lambda\pi^-$, $pN \to \overline{\Xi}^+ X, \overline{\Xi}^+ \to \overline{\Lambda}\pi^+$	$(0.0 \pm 5.1 \pm 4.4) \times 10^{-4\dagger}$	[14]

‡Based on ≈5% of the total HyperCP dataset.

It is difficult to see how the HyperCP approach can be extrapolated to 10^{-5} sensitivity. However, the approach of PS185 may yet have significant "headroom" [16]. In 1992, Rapidis, et al. (P859) proposed to look for CP violation in the α parameter of Λ decay using the reaction $\overline{p}p \to \overline{\Lambda}\Lambda$ with a hydrogen gas jet target and a $\overline{p}$ beam energy of 1.641 GeV/c (above threshold for $\overline{\Lambda}\Lambda$ but below threshold for $\overline{\Lambda}\Sigma$). The experiment proposed building a small storage ring which could accept 3 GeV/c antiprotons from the Accumulator and decelerate them to the desired energy. The proponents of P859 estimated that they could reach a sensitivity of 10^{-4} in the fractional difference between the Λ and $\overline{\Lambda}$ α parameters in three months of running, consuming 6 mA of $\overline{p}$ current from the Accumulator per hour.

Since 1992, the HyperCP experiment, which was also designed to study CP violation in hyperon decays (either Λ or Ξ) has been run. HyperCP has not yet published its final result, but it is likely that this experiment will achieve a sensitivity close to the 10^{-4} level that was the goal of P859.

If systematics can be handled, it might be possible to reach the 10^{-5} level using the technique proposed by P859. This would require 100 times more events, but this sample could be collected in a few years, even assuming that the experiment used only one half of the total number of antiprotons provided by the antiproton source (assuming a stacking capacity of 80 mA/hour).

4 Stopping Antiprotons

Experiments have been done at CERN with stopping antiproton beams for many years. Recently, the two antihydrogen experiments running at the Antiproton Decelerator have received significant coverage in the popular press as they succeeded in producing antihydrogen atoms (but not yet storing the atoms) in Penning traps. A third experiment running at the AD is studying antiprotonic Helium. It is unlikely that a convincing argument will be made that Fermilab should duplicate the effort already made at CERN by building a storage ring capable of decelerating a significant number of antiprotons, especially if GSI decides to include such a facility in their new antiproton physics program.

5 Prototype Neutrino Factory

In normal operation of the antiproton source, pions as well as antiprotons are captured by the Debuncher. The decay chain $\pi \to \mu \to e$ yields:

- $\overline{\nu_\mu}$'s from pion decays, and
- ν_μ's and $\overline{\nu_e}$'s from muon decays.

Pions circulate in the Debuncher for no more than a few turns; most decay in the first turn. Muons from pion decay are captured only if their momentum is very close to the parent pion momentum. The V-A nature of the decay means that the captured muons are spin polarized. The muon spin precesses as the muons circulate in the Debuncher so that the spin direction is a function of the turn number. If one concentrates on decay neutrinos emitted in the forward direction from a particular machine straight section, then the V-A nature of the muon decay means that ν_μ's and $\overline{\nu_e}$'s appear separated in time.

These features of the neutrinos created in normal operation of the antiproton source have been pointed out before. They formed the basis of Proposal 860. The number of muons captured in the Debuncher has been measured and is approximately equal to the number of antiprotons captured (reference). The prompt $\overline{\nu_\mu}$'s have a sharply peaked energy distribution with an endpoint of 4 GeV and a width determined by the angular definition of the beam. The ν_μ's and $\overline{\nu_e}$'s have broad energy distributions peaked at roughly 4.5 GeV. The number of neutrinos produced in this manner into a cone of a given solid angle is much smaller than can be produced in a conventional neutrino beam, and it is unlikely that a competitive experiment could be mounted using such a beam, but it has been pointed out (ref: John Cooper) that the time separated nature of this beam could make it especially valuable as a test beam for validating neutrino detector designs.

If the antiproton source were no longer needed full-time for producing antiprotons, a number of options would open up:

- The polarity of the Debuncher could be reversed, so that positive pions and muons are captured. This would result in a prompt ν_μ beam and time separated $\overline{\nu_\mu}$'s and ν_e's.
- The Debuncher could be operated using either polarity at a low energy to collect pions created using a lower energy proton beam. This could be the 8 GeV proton beam, or a Main Injector beam with energy between 8 and 120 GeV and repetition rate correspondingly faster than is possible at 120 GeV.
- The Debuncher could be operated using either polarity at a low energy to store muons prepared by a prototype muon source.

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